PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Faulting and Graben Formation in Western and Central Europe [and Discussion]

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Faulting and graben formation in western and central Europe

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Rifts and rift-related basins play a pre-eminent role among the sedimentary basins of western and central Europe. Through time, grabens developed in a number of different megatectonic settings whereby the principal mechanisms governing their subsidence was crustal stretching and 'subcrustal erosion'. The level of volcanic activity associated with rifting is highly variable and can change significantly during the development history of a rift. Some rifts are totally non-volcanic. The development of rift domes is generally associated with volcanic activity. Uplifting of a rift dome can induce a reversal in the subsidence pattern of a rift. Intracontinental rifts, with their thinned crust, are prone to inversion when the respective craton is subjected to tangential stresses. In the process of inversion the crust of rifts is mechanically thickened again.

1. Introduction

Rifts play a pre-eminent role among the sedimentary basins of western and central Europe. Several more or less distinct rifting cycles can be distinguished whereby the formation of grabens took place in a number of different megatectonic settings.

Back-arc rifting played a significant role during the Devonian and early Carboniferous development of the Variscan geosynclinal system. Essentially wrench-induced pull-apart features developed during the Devonian and early Carboniferous sinistral translation between Laurentia–Greenland and Fennoscandia–Baltica as well as during the late Variscan dextral translation between Europe and Africa. Regional crustal extension, preceding continental splitting and the onset of seafloor spreading, was the dominant mechanism that governed the development of the Carboniferous and Mesozoic Arctic – North Atlantic rift and of the Mesozoic rifts of western and central Europe. Mechanisms controlling the Neogene collapse of the Mediterranean basins and the development of Oligocene and younger rifts in the northern Alpine foreland are still the subject of dispute.

During the Variscan and Alpine orogenic cycles a number of the previously formed graben became deformed and inverted in response to compressional stresses transmitted through the foreland crust of the respective fold belts.

In the following a summary is given of the development of the various graben systems of western and central Europe. For a more detailed discussion, including comprehensive literature indexes, the reader is referred to Ziegler (1978*a*, *b*, 1980, 1981) and to the *Geological atlas of western and central Europe* that is currently in preparation (Ziegler 1982).

2. Variscan Geosynclinal System, a case of back-arc rifting?

The late Caledonian framework of the North Atlantic domain is summarized in figure 1, while figures 2 and 3 provide an overview of its mid-Devonian and early Carboniferous setting.

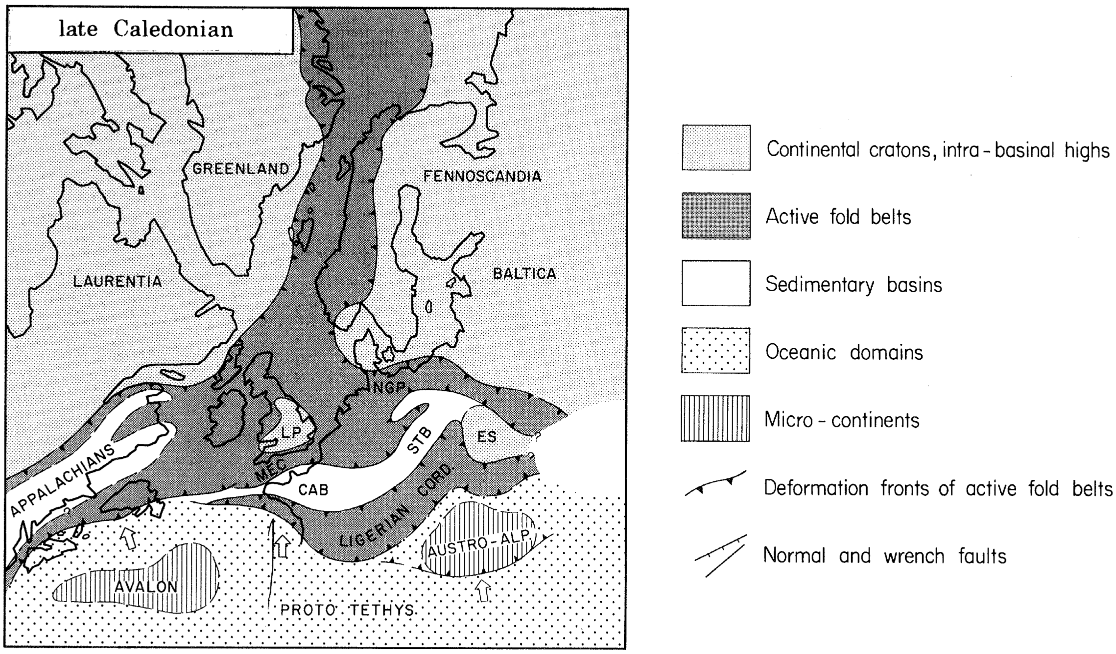

FIGURE 1. Schematic late Caledonian tectonic map of the North Atlantic area.

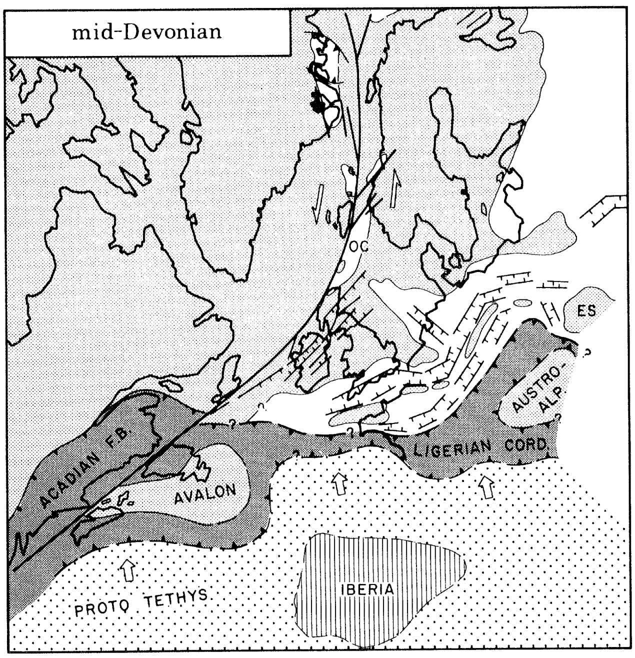

FIGURE 2. Schematic mid-Devonian tectonic map of the North Atlantic area.
For key see figure 1.

The Precambrian and Caledonian micro-cratons of the London Platform, Central Armorica, Moldanubia and East Silesia, which were apparently rifted off the northern margin of Gondwana during Cambrian and Ordovician time, were accreted in the course the late Ordovician and Silurian to the southern margin of Fennoscandia–Baltica. By late Silurian – early Devonian time much of western and central Europe was occupied by Caledonian fold belts. Only in the

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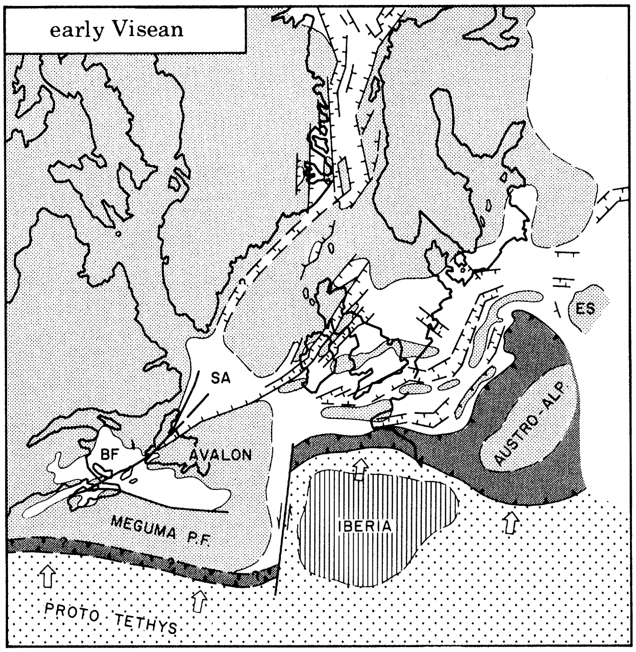

FIGURE 3. Schematic early Carboniferous tectonic map of the North Atlantic area. For key see figure 1.

TABLE 1. ABBREVIATIONS USED ON THE FIGURES

AA	Austro-Alpine Block
AB	Altmark–Brandenburg Basin
ALH	Alemanic High
BC	Bristol Channel Trough
BF	Bay of Fundy Basin
BU	Brugundy Trough
CA	Cardigan Bay Trough
CAB	Central Armorican Basin
CB	Channel Basin
CG	Central Graben
CN	Central Netherlands Basin
CS	Celtic Sea Basin
DB	Dublin Trough
DT	Danish Trough
EB	Egersund Basin
EC	East Carpathian Gate
ES	East Silesian
ET	Emsland Trough
GG	Glückstadt Graben
GRLD	Greenland
HB	Horda Basin
HD	Hessian Depression
HF	Haig–Fras Depression
HG	Horn Graben
HP	Hampshire Basin
KB	Kish Bank Basin
LS	Lower Saxony Basin
LP	London Platform
MA	Mendip Axis
MB	Minch Basins
MC	Massif Central
MEC	Mid European Caledonides
MF	Moray Firth Basin
NGP	North German–Polish Caledonides
MM	Morton-in-the March Axis
MNH	Mid-North Sea High
MW	Market Weighton Axis
MX	Manx-Furness Basin
NF	Normandy Fault
PB	Paris Basin
PC	Porcupine Trough
PD	Pays-de-Bray Fault
PS	Pompeckj Swell
PT	Polish Trough
RFH	Ringkøbing–Fyn High
RM	Rhenish Massif
SA	Saint Antony Basin
SE	Slyne–Erris Trough
SH	Sub-Hercynian Basin
SM	Silesian-Moravian Gate
SP	Sole Pit Basin
SS	Saxonian Strait
ST	Sticklepath Fault
STB	Saxothuringan Basin
TB	Trier Bay
UB	Ulster Basin
VG	Viking Graben
WA	Western Approaches Trough
WG	Worcester Graben
WM	Welsh Massif
WN	West Netherlands Basin

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Central Armorican–Saxothuringian successor basin and in the East Sudetic area did marine sedimentation continue across the Silurian–Devonian boundary. These basins were underlain by thinned continental crust. The Ligerian–Moldanubian Cordillera was associated with the north-plunging Proto-Tethys (Rheic) subduction zone.

Following the late Silurian – early Devonian late Caledonian diastrophism the evolution of areas to the north of the Ligerian-Moldanubian Cordillera was characterized by tensional tectonics. In the area of the rapidly degraded Mid-European and North German–Polish Caledonides the Cornwall–Rhenish–East Sudetic Basin began to subside rapidly during the early Devonian. Crustal extension persisted through the mid and late Devonian into early Carboniferous time whereby block faulting controlling facies patterns was associated with a distinctly bimodal felsic–mafic alkaline volcanism (Ziegler 1978*b*; Sawkins & Burke 1980).

As such the Cornwall–Rhenish–East Sudetic Basin can be regarded as a complex rift system. Details of its configuration are, however, difficult to unravel owing to its strong deformation during the late Carboniferous Variscan diastrophism and the lack of a reliable palispastic restoration of this fold belt.

The Normannian–Mid-German High separated the Cornwall–Rhenish Basin from the southward adjacent Central Armorican–Saxothurigian Basin. The Devonian and early Carboniferous development of the latter reflects the interplay of tensional and compressional tectonics. Periods of extension induced basin subsidence and the repeated outpouring of alkaline bimodal volcanics. During periods of compression, rift-related volcanic activity was interrupted.

The early Middle Devonian Acadian–Ligerian diastrophism, which marked the collision of the Avalon and Austro-Alpine micro-cratons with Laurasia, is strongly expressed in the Ligerian–Moldanubian Cordillera but affected only the southern margin of the Central Armorican–Saxothuringian Basin (Autran & Cogné 1980). This orogenic event was followed by a renewed tensional accentuation of the Central Armorican–Saxothuringian successor basin and correspondent volcanic activity. At the transition from the Devonian to the Carboniferous the Bretonian diastrophism, which strongly affected the Ligerian–Moldanubian Cordillera, caused minor folding and a temporary interruption of the rift volcanism in the Central Armorican–Saxothuringian Basin. During the early Visean this basin became once more accentuated by tensional tectonics. With the late Visean onset of the Sudetic diastrophism, the Central Armorican–Saxothuringian Basin became progressively filled with the synorogenic Culm flysch deposits. By latest Visean time this successor basin became folded, uplifted and partly destroyed.

In the Cornwall–Rhenish–East Sudetic Basin the last pulse of rift-related volcanism occurred during the early Visean. During the late Visean underthrusting began along the northern margin of the Normannian–Mid-German High and initiated the shedding of coarse clastics into the Cornwall–Rhenish–East Sudetic Basin where they were deposited as the synorogenic Culm flysch. At the same time the axis of this basin was shifted to the south, presumably in response to tectonic loading of the foreland by the advancing thrust sheets. With this the Cornwall–Rhenish–East Sudetic Basin assumed the asymmetric geometry of a classical foredeep. During the late Carboniferous the axis of this foredeep migrated northward as a consequence of the advancement of the Variscan deformation front. By late Namurian time sedimentation exceeded subsidence rates and paralic conditions were established along the southern basin margins as topsets of large clastic fans that prograded northward into its deeper parts. With the onset of the Westphalian a paralic, molasse-type, depositional régime was established throughout the Variscan foredeep basin (Paproth & Teichmüller 1961; Teichmüller 1973). Last compressional deformations are dated as late Westphalian – early Stephanian (Asturian phase).

The Devonian and early Carboniferous evolution of the Variscan geosynclinal system can be explained in terms of back-arc rifting. Back-arc rifting and sea-floor spreading is thought to occur if the subducting and overriding plates diverge or if their convergence rates decrease below the level at which partial coupling occurs between them at the Benioff zone (Uyeda 1981; Hsui & Toksöz 1981).

After the late Caledonian diastrophism these conditions were apparently fulfilled between Laurasia and the subducting Proto-Tethys plate. Back-arc rifting set in during the early Devonian and persisted till early Visean time. It affected wide areas to the north of the Ligerian–Moldanubian Cordillera but apparently never proceeded to the point of crustal separation and the opening of back-arc oceanic basin. Back-arc rifting was partly contemporaneous with a major mid-Devonian to early Carboniferous sinistral displacement between Laurentia–Greenland and Fennoscandia–Baltica (see below).

Temporary partial coupling at the Proto-Tethys B-subduction zone during the Acadian and Bretonian orogenies was apparently strong enough to interrupt rifting in the Central Armorican–Saxothuringian Basin but did not affect the Cornwall–Rhenish–East Sudetic Basin.

The onset of the late Visean Variscan main orogeny presumably reflects an increase in the convergence rate between the Laurasian and Proto-Tethys plates. This was followed by the collision of Iberia and later also of Gondwana with Laurasia. Resultant regional compressive stresses caused the sharp termination of back-arc rifting and the scooping-out of the back-arc basins by thrust sheets and nappes.

3. Devonian and Carboniferous Arctic – North Atlantic wrench and rift system

The early Devonian development of the Arctic – North Atlantic Caledonides was characterized by their rapid erosion, isostatic uplifting and a post-orogenic calc-alkaline plutonism. From mid-Devonian until early Dinantian time wrench-tectonics related to a sinistral displacement between Laurentia–Greenland and Fennoscandia–Baltica amounting to 1500–2500 km dominated the evolution of the Arctic – North Atlantic area (Morris 1976; Kent & Opdyke 1979; Van der Voo & Channel 1980).

This is illustrated by the evolution of the partly fault-bounded intramontane Old Red 'Molasse' basins of Svalbard, Eastern Greenland, Western Norway and the British Isles. Subsidence of these basins was accompanied by syndepositional wrench-related compressional deformations. Earliest compressive movements are dated as mid-Devonian and are thus contemporaneous with the Acadian-Ligerian diastrophism, while the last compressional deformations are dated as early Dinantian (Haller 1971; Harland 1978). From Visean time onward the development of the Arctic – North Atlantic realm was governed by tensional tectonics. This is illustrated by the evolution of eastern Greenland and the Svalbard–Barents Sea area where thick Carboniferous and younger strata accumulated in complex graben systems (Vischer 1943; Haller 1971; Harland *et al.* 1974; Rønnevik 1981).

In the area of the future Norwegian–Greenland Sea, crustal extension persisted from late early Carboniferous time over some 270 Ma until crustal separation was achieved during the late Palaeocene. In this rift system the level of volcanic activity was extremely low during late Palaeozoic and Mesozoic times but increased sharply immediately before crustal separation.

4. Devonian and Carboniferous rifts of the British Isles

In the British Isles the Orcadian Basin, the Midland Valley Graben and the Northumberland–Solway–Dublin Trough started to subside rapidly during the early Devonian. Lower Old Red clastics reach thicknesses of 2.5 km in the Orcadian Basins and 6.6 km in the Midland Valley Graben (House *et al.* 1977). Subsidence of these basins was accompanied by widespread calc-alkaline intrusions and an intense felsic to mafic volcanism. The mid-Devonian deformation of these basins is thought to reflect the onset of transpression along the Arctic – North Atlantic transform system. In the Midland Valley Graben and the Northumberland–Solway–Dublin Trough the mid-Devonian corresponds to a regional unconformity, while in the Orcadian Basin Middle Old Red clastics are up to 5 km thick. Rapid subsidence of the Orcadian Basin as well as the syndepositional deformation of its sedimentary fill reflects the interplay between tensional and compressional stresses associated with sinistral translation of major proportions along the Great Glen fault (Van der Voo & Scotese 1981).

In the course of the late Devonian sedimentation was resumed in most of the Old Red Basins of northern and central Britain and Ireland. Volcanic activity was at a low level and subsidence rates were generally relatively low.

Sedimentation was continuous across the Devonian–Carboniferous boundary (George *et al.* 1976; Francis 1978*a*). During the Dinantian the Midland Valley Graben and the Northumberland–Solway–Dublin Trough continued to subside differentially, although the Orcadian Basin became largely inactive. At the same time the Craven Basin began to subside rapidly. Sharp lateral facies and thickness changes are indicative of syndepositional tensional faulting (Leeder 1974; George 1958). Locally this was accompanied by an early Dinantian alkaline, mafic–felsic bimodal volcanism. In the course of the late Namurian and early Westphalian the individual grabens gradually ceased to subside differentially and rift-related volcanic activity abated (Francis 1978*b*). During the late Westphalian the sedimentary fill of these tensional basins became folded and uplifted to various degrees (inversion). Owing to the ensuing erosion of the Carboniferous strata it is not clear whether these rifts had become inactive altogether before their inversion. In spite of an incomplete Permian and younger stratigraphic record these rifts appear to have reached thermal and isostatic equilibrium through their inversion.

The Devonian and Carboniferous rifts of the central and northern British Isles occupy an intermediate position between the back-arc rifts of the Variscan geosynclinal system and the Arctic – North Atlantic wrench–rift system.

The rapid early Devonian subsidence of the Midland Valley and the Northumberland–Solway–Dublin grabens parallels the development of the Cornwall–Rhenish–Lower Silesian and the Central Armorican–Saxothuringian basins and may also be related to back-arc extension. During the mid and late Devonian the development of the rifts of the central and northern British Isles was dominated by the Arctic – North Atlantic translation. Crustal extension resumed, however, at the onset of the Carboniferous and persisted into late Carboniferous times, while rifting in the Variscan geosynclinal system ceased with the late Visean onset of regional compression. In contrast, the development of the Barents Sea and Norwegian–Greenland Sea area was governed from late Visean time onward by crustal extension. In this respect the Carboniferous rifts of Ireland and the United Kingdom as well as the St Anthony and the Bay of Fundy basins of the Canadian Maritime Provinces (Howie & Barss 1975) could be regarded as forming part of the Arctic – North Atlantic rift system.

While rifting persisted in the Norwegian–Greenland and Barents Sea area throughout the late Carboniferous, crustal extension abated in the British Isles. During the late Westphalian terminal phases of the Variscan orogeny tangential stresses were transmitted through the foreland crust and caused the transpressional deformation and partial inversion of these grabens and troughs at considerable distances to the north of the Variscan thrust-front.

5. Late Variscan wrench and rift tectonics

Following the late Westphalian – early Stephanian consolidation of the Variscan fold belt convergence between Gondwana and Laurasia apparently changed from an essentially north–south-directed collision to an east–west-oriented one. Orogenic movements continued during Stephanian and Autunian time in the Appalachian–Mauretanides and in the Uralides, whereas the Variscides remained inactive. This was accompanied by the development of a right lateral transform system that linked the southern Uralides with the northern Appalachians via Europe where it caused the development of a complex pattern of conjugate shear faults and related pull-apart structures (Arthaud & Matte 1977). This fault system remained active until the late early Permian consolidation of the Appalachians–Mauretanides and the Uralides

Main elements of the late Variscan fracture system of northern Africa and Europe are summarized in figure 4. Displacements along the Kelvyn–Agadir and the Chedabucto–Gibraltar faults were compensated for by wrench and compressional deformations in the northern Appalachians and by the inversion of the Carboniferous troughs in the Canadian Maritime provinces (Rast & Grant 1977; Schenk 1978). Displacements along the Bay of Biscay fault system were partly taken up in the Arctic – North Atlantic rift in which crustal distension persisted through late Carboniferous and Permian time. Right lateral wrench movements along the Tornquist–Teisseyre lineament, at its northern termination, induced the development of the Oslo–Bamble–Horn Rift.

Areas located between the Agadir fault zone and the Tornquist–Teisseyre lineament became transected during the Stephanian and Autunian by a network of subsidiary wrench and tensional faults (figure 5). This was accompanied by the rapid subsidence of narrow wrench-related basins and the extrusion of often thick volcanics. Examples of such wrench basins, in which several thousand metres of coal-bearing clastics were deposited, are the St Étienne, Lodève and Cévennes basins in the Massif Central. Extensive late Carboniferous to early Permian volcanics occur in the subsurface of northern Germany and Poland and reach thicknesses up to 2 km. Volcanic centres appear to coincide with the intersection of fault systems and are probably related to pull-apart structures at the termination of subsidiary wrench faults paralleling the Tornquist–Teisseyre line. The latter is not represented by a single major fracture but corresponds to a broad essentially northwest–southeast striking fault zone. In the western Baltic and in the Kattegat, where it is referred to as the Fennoscandian Border Zone, the pattern of this fault system is strongly suggestive of strike-slip displacement. Associated dyke swarms permit dating of faulting as late Carboniferous to early Permian.

In this area the early Palaeozoic shelf sediments of the Caledonian foreland were strongly dissected whereby up to 4 km thick Cambro-Silurian sediments are preserved in narrow down-faulted blocks, while in adjacent upthrown blocks the entire section is missing owing to late Palaeozoic and Mesozoic erosion (see Ziegler 1978*a*, encl. 1).

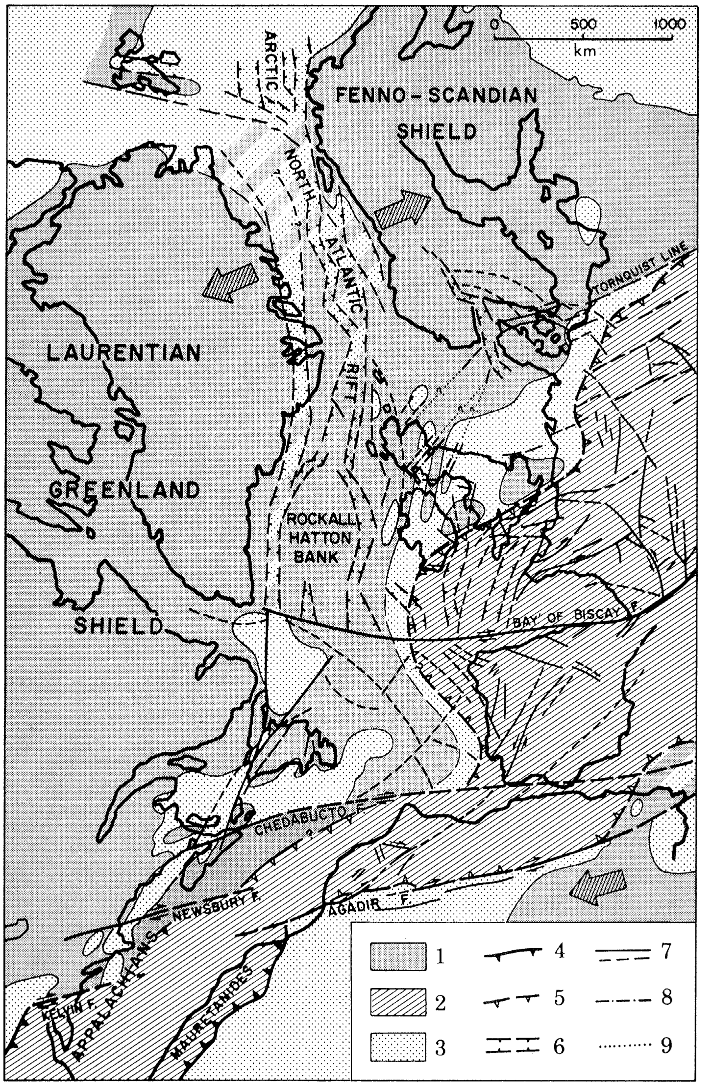

FIGURE 4. Schematic late Variscan tectonic map of the North Atlantic area: 1, pre-Variscan stable elements; 2, Variscan fold-belt; 3, Carboniferous basins in Variscan foreland; 4, Alleghenian deformation front; 5, Asturian deformation front; 6, grabens, rifts; 7, faults; 8, dyke swarms; 9, alignments.

The Oslo–Bamble–Horn Graben, which marks the northwestern termination of the Tornquist–Teisseyre line, came into evidence during the latest Westphalian to Stephanian. Igneous activity started in the southern Oslo Graben and gradually spread northward and presumably also southward. This probably reflects rift development by fracture propagation. In view of its relation to the Tornquist–Teisseyre line, the Oslo–Bamble–Horn Graben can be considered as a pull-apart feature at the termination of a transcurrent fault, rather than

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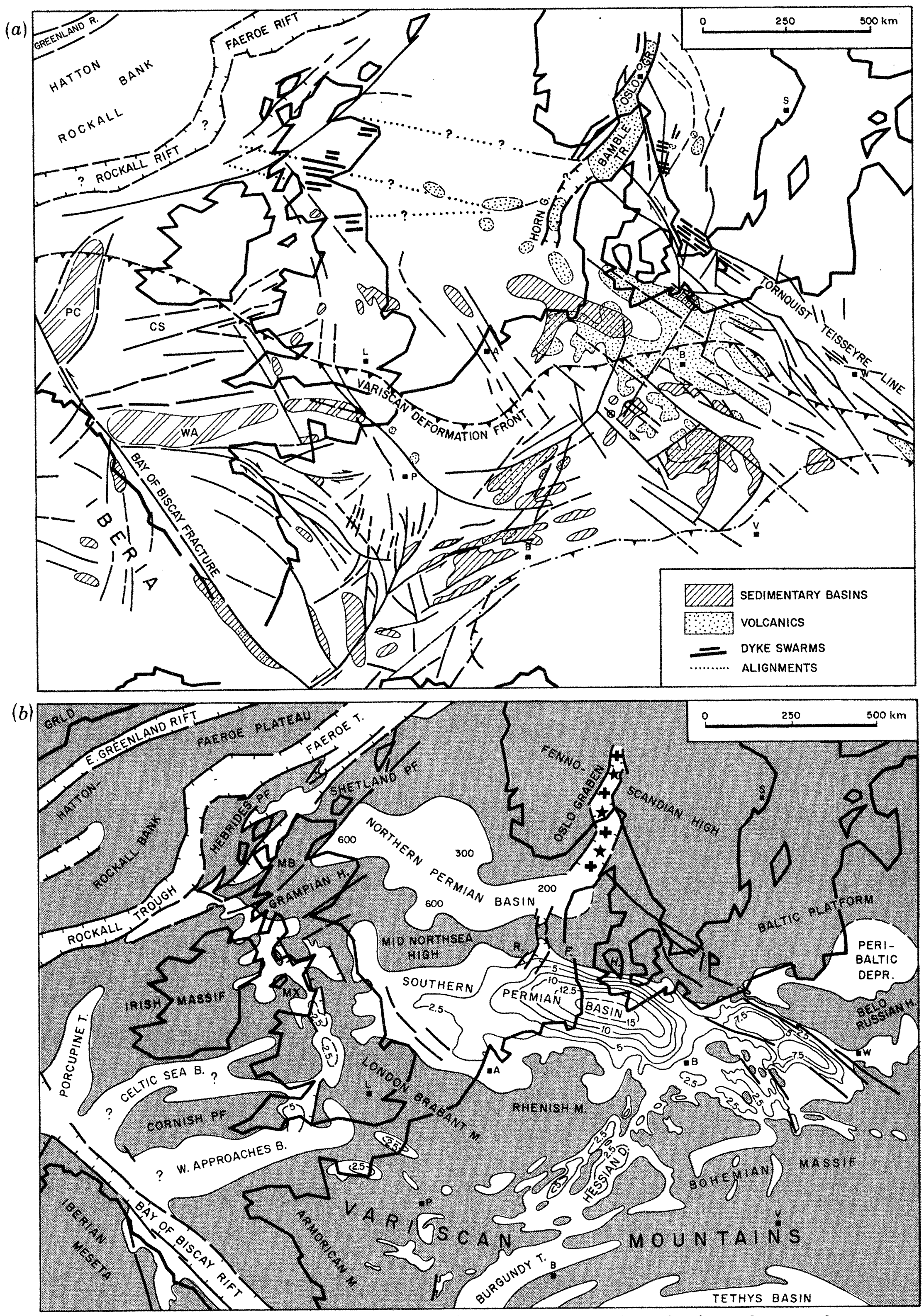

FIGURE 5. (*a*) Stephanian–Autunian fault patterns. (*b*) Tentative isopach map of Rotliegend sediments, contour values in hundreds of metres; thickness values in metres.

as a mantle plume-induced rift. Although crustal distension terminated in the Oslo Graben with the onset of the Saxonian, magmatic activity persisted until late Permian time.

Permian volcanics in the Oslo Graben display a typical mafic–felsic bimodality and are highly alkaline (Oftedahl 1968; Ramberg 1976). A similar alkaline bimodality characterizes the Lower Permian volcanics of the central North Sea area (Dixon *et al.* 1981). In the immediate foreland of the Variscan fold belt, Lower Permian volcanics are only mildly alkaline, with mafic rocks predominating (Eckhardt 1979). In the domain of the Variscan fold belt, Lower Permian volcanics display the typical calc-alkaline composition of a late to post-orogenic volcanism (Kramer 1977).

In the central and northern North Sea and along the Scottish–Irish Atlantic seaboard the importance of the Stephanian–Autunian faulting is difficult to assess because much of the area was apparently uplifted during this time. Clear evidence of late Westphalian – early Stephanian tectonic activity is provided by the intrusion of east–west striking tholeiitic dyke swarms that transect the Midland Valley Graben and the Northumberland Trough (Francis 1978*b*). Furthermore a dyke swarm of late Carboniferous to early Permian age that transects the Great Glen Fault in the West Scottish Argyll area indicates that by this time all sinistral translation along this fault had ceased (Speight & Mitchell 1978). In the Firth of Clyde and Solway Firth area (southern Scotland) the border faults of several small Stephanian–Autunian basins clearly transect Devonian and Carboniferous structural trends (Brookfield 1978).

This limited evidence indicates that the tectonic setting of the northern British Isles had also undergone a profound modification during the latest Carboniferous and early Permian.

At the onset of the Saxonian (late early Permian), the late Variscan wrench and pull-apart system became inactive. While the Variscan fold-belt was isostatically uplifted, two large sedimentary basins, referred to as the Northern and Southern Permian basins, began to subside in its foreland.

During the Saxonian the continental Rotliegendes redbeds accumulated in these basins (figure 5). Subsidence rates exceeded sedimentation rates and caused the development of topographic depressions that were located below the level of the world oceans. At the onset of the Thuringian these basins were flooded by the transgressing Arctic seas. This was followed by the accumulation of thick Zechstein carbonate, sulphate and halite series. Isostatic adjustment of the crust, initially to water loading and later to sediment loading, caused further subsidence and the progressive overstepping of the basin margins. At the end of the Permian, subsidence and sedimentation rates were in balance.

The geometry of the Northern and Southern Permian basins reflects regional downwarping of the crust whereby faulting played only a minor role. In the Southern Permian Basin, Permian strata attain a maximum thickness of 3.5 km, while in the Northern Permian Basin they do not exceed 1.5–2 km.

Isopach maps of the Rotliegendes series show that two subsidence centres occurred in the Southern Permian Basin (figure 5). The western subsidence maximum coincides with the area of extensive Autunian volcanism in northern Germany, while the eastern one is superimposed on the Polish part of the Tornquist–Teisseyre lineament. Cooling of a late Carboniferous – early Permian thermal anomaly may explain the subsidence of the north German depocentre, whereas to explain the subsidence pattern of the Polish sub-basin, limited crustal extension, possibly related to early rifting phases in the Tethys, may have to be invoked. On the other hand, lateral ductile flow in the upper mantle, possibly induced by the isostatic uplift of the Variscan fold belt and its thickened lithosphere, may also have played a role in the subsidence of this basin. In this respect a parallel can be drawn between the megatectonic setting of the Southern Permian Basin relative to the Variscan fold belt and the Black Sea relative to the Alpine fold belt; both basins have a similar areal extent and both can be considered as post-orogenic foreland collapse basins.

The geometry of the Northern Permian Basin is difficult to decipher owing to its strong overprinting by Mesozoic rift tectonics. Mechanisms governing its subsidence remain enigmatic. While the Oslo Graben, in which magmatism persisted until late Permian time, did not show any evidence of differential subsidence, the Horn Graben and possibly also the Bamble Trough did begin to subside during the Thuringian.

6. Mesozoic rift systems

After its temporary Permian consolidation the Pangaean supercontinent was again showing signs of inherent instability during the late Permian and even more so during the Triassic. This was manifested initially by the reactivation of the pre-existing peripheral Arctic – North Atlantic rift system and by the inception of the Gondwana rifts but later also by the development of new, interior rift systems. In the course of the Triassic Pangaea became transected in a north–south direction by the Arctic – Central Atlantic rift and in an east–west direction by the Tethys – Central Atlantic – Gulf of Mexico rift–wrench system (Dewey *et al.* 1973; Laubscher & Bernoulli 1977; Biju-Duval *et al.* 1977).

Both of these mega-rifts flanked the already deeply fractured metastable platform of western and central Europe which became affected as a whole by regional tensional stresses. This gave rise to the subsidence of a multidirectional system of grabens and troughs that partly reflects the reactivation of late Carboniferous – early Permian faults.

This rift system remained active until crustal separation was achieved in the Iceland and Norwegian–Greenland Sea during the late Palaeocene. However, the progression of crustal extension and the onset of sea-floor spreading in the central Atlantic and in the western Neo-Tethys during the mid-Jurassic, and in the North Atlantic and the Bay of Biscay during the early Cretaceous, in time caused a reorientation of the stress systems that affected western and central Europe (figure 6). This resulted in a polarization of its rift systems in the course of which a number of Triassic and Jurassic grabens became inactive. Major tectonic events affecting the Atlantic and Tethys rift systems are also reflected in the stratigraphic record of the Mesozoic basins of western and central Europe.

(*a*) *Triassic rifts*

In western and central Europe, Triassic series consist of continental redbeds, evaporites and shallow marine sediments. As sedimentation rates generally kept pace with subsidence rates, isopachs of their depositional thickness give a fair image of the overall subsidence pattern of the Triassic basins. From figure 7 it is evident that the Northern and Southern Permian Basin continued to subside during the Triassic along lines established during the Permian. However, their framework became modified by the development of the North Sea rift system, the Polish–Danish Trough and a number of subsidiary grabens such as the Horn and Glückstadt Graben, the Emsland Trough and the Hessian Depression. Triassic series reach a thickness of over 4 km in the Polish–Danish Trough and in the Glückstadt Graben and some 3 km in the northern Viking Graben.

The Viking and Central Graben as well as the Horda–Egersund half-graben began to subside during the early Scythian. These rifts, developed presumably by fracture propagation of the East Greenland – Western Norway rift in response to accelerated crustal extension in the Arctic – North Atlantic domain (figure 6).

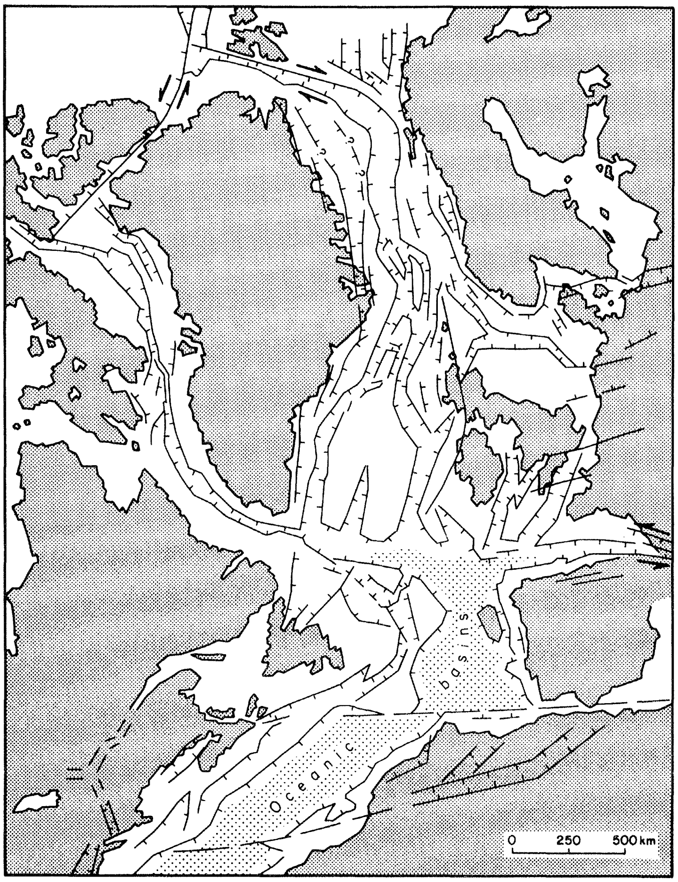

FIGURE 6. Schematic pattern of Mesozoic Arctic – North Atlantic rift system (continental fit approximately early Cretaceous).

Differential subsidence of the Minches, West Hebrides and West Shetland half grabens and probably also of the Rockall – Faeroe Rift, which had set in during the late Permian, persisted through Triassic time. In the Minches Graben, poorly dated Permo-Triassic redbeds reach a thickness of some 4 km.

The Bay of Biscay Rift subsided relatively slowly during the early and mid-Triassic but considerably faster during the late Triassic. Accelerated subsidence was accompanied by the widespread extrusion of basaltic volcanics. This volcanic activity was probably induced by contemporaneous left-lateral wrench movements that compensated for differential crustal stretching in the Newfoundland–Lusitania Rift and in the rifts on the Irish and French shelves. The latter include the Porcupine, Celtic Sea, Bristol Channel and Western Approaches troughs. Differential subsidence of these graben probably started during the Permian but became pronounced during the Triassic. In the Celtic Sea and Western Approaches troughs,

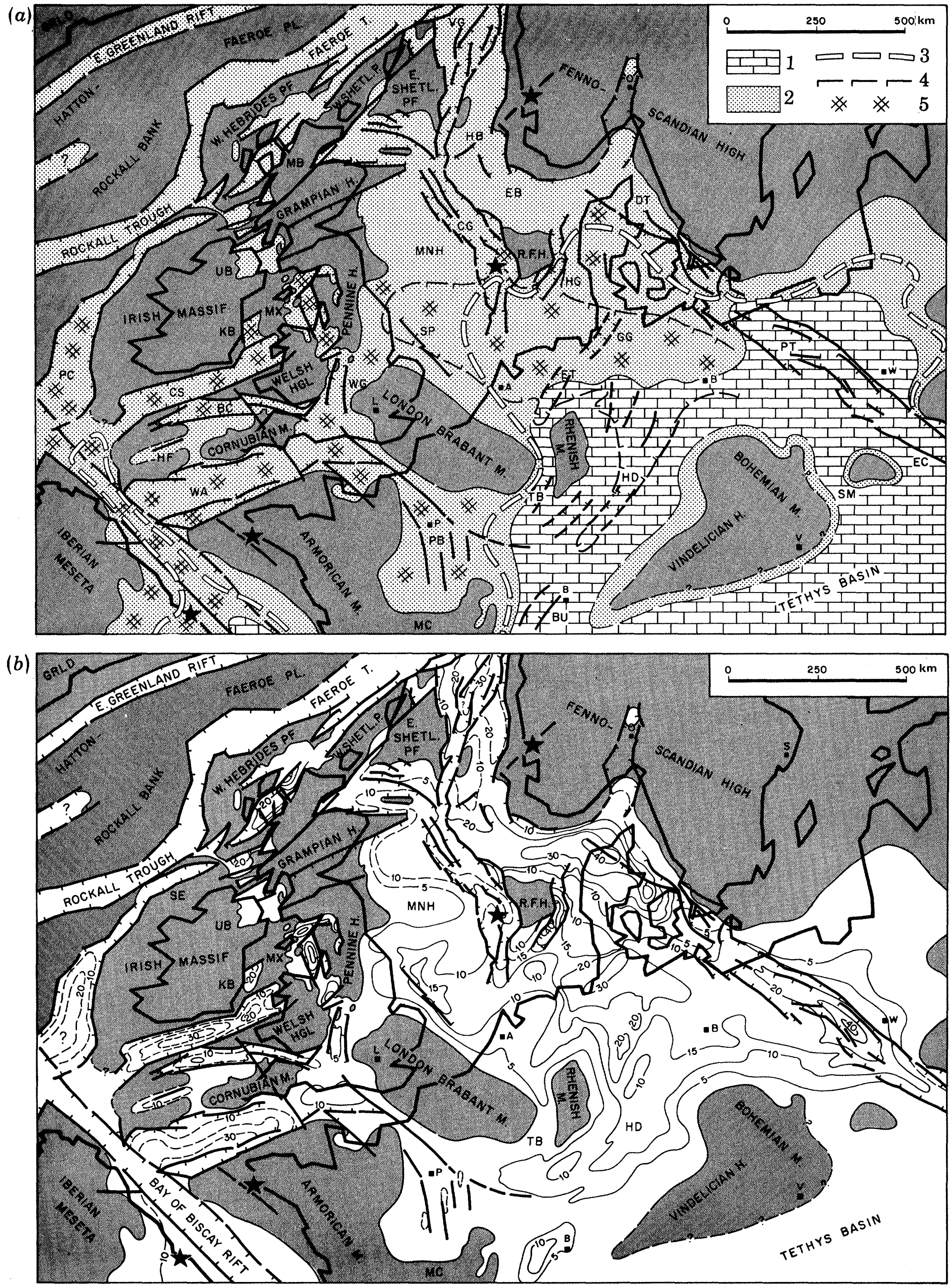

FIGURE 7. (*a*) 1, Distribution of massive Muschelkalk; 2, maximum distribution of Triassic strata; 3, depositional edge of Muschelkalk; 4, distribution of Röt salt; 5, Keuper salts. (*b*) Tentative isopach map of depositional thickness of Triassic sediments. Contour values in hundreds of metres.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Triassic series exceed a thickness of 3 km and in the Porcupine and Bristol Channel some 2 km. The western Approaches, Bristol Channel and Celtic Sea troughs are cut off to the east by a system of wrench-faults that strike into the Paris Basin (Sticklepath, Normandie–Sennely and Pays-de-Bray faults).

The Worcester Graben, The Cheshire and Manx-Furness, the Kish Bank, Solway-Vale-of-Eden and the Ulster Basin may be interpreted as forming the northern continuation of this complex wrench and pull-apart system that compensated for crustal dilatation taking place in the Celtic Sea, Bristol Channel and Western Approaches grabens.

The Triassic rifts of western and central Europe are essentially non-volcanic; the wrench-related Aquitaine Basin is an exception. Only very minor Triassic volcanics are reported from the west coast of Norway (Faerseth *et al.* 1976) from the Central Graben where it intersects the mid North Sea and the Ringkøbing-Fyn High and from the south coast of Brittany.

The extremely low level of volcanic activity associated with the Triassic rifts of western and central Europe is all the more surprising as their dimensions compare readily with those of the highly volcanic Cainozoic Rhine Graben system, or for that matter with parts of the East African Rift. This indicates that the Triassic rift system of western and central Europe subsided in response to regional crustal extension rather than owing to the development of a multitude of local hotspots or mantle plumes. Major rift domes, the telltale signs of mantle plumes, are conspicuously lacking from the Triassic scene of western and central Europe.

(*b*) *Jurassic polarization of rift system*

In the course of the early Jurassic a relative sea level rise induced the transgression of the Arctic and Tethys seas and their linking up through the rift systems of western and central Europe. These graben and troughs continued to subside during early Jurassic times along patterns established during the Triassic without any evidence for discrete rifting pulses. With the exception of minor Rhaeto-Liassic tuffs in the Aquitaine Basin there is no evidence for early Jurassic volcanism in western and central Europe (figure 8).

At the passage from the early to the mid-Jurassic, tectonic activity increased in the Arctic Central Atlantic and the Tethys rift systems. In the Central Atlantic and in the Western Tethys this induced crustal separation. This major tectonic event was apparently accompanied by a eustatic lowering of the sea level (Vail *et al.* 1977; Hallam 1978).

In northwest Europe this major rifting pulse, which is referred to as the Mid-Cimmerian tectonism, gave rise to the uplifting of a large rift dome in the central North Sea (figure 8). The crest of this dome was transected by the Central Graben. At the triple junction of the Central Graben, the Viking Graben and the Moray Firth fault system a large volcanic centre was initiated. Subsidiary volcanic centres occurred in the Viking Graben and the Egersund Basin as well as in the Sunn Hordland area of western Norway. Most of these volcanics were extruded during the Bajorcian. They display the alkaline bimodal chemistry that is typical for continental rifts (Dixon *et al.* 1981). Uplifting of the central North Sea rift dome, which had a structural relief of 2–3 km, was probably induced by the emplacement of a low density asthenolith at the crust–mantle interface.

Uparching of this rift dome induced drastic palaeogeographic changes in northwest Europe. While early Jurassic and older strata were deeply truncated over the crest of this dome, erosion products were shed northward into the continuously subsiding Viking Graben and southward into the incipient Sole Pit, West and Central Netherlands and Lower Saxony basins.

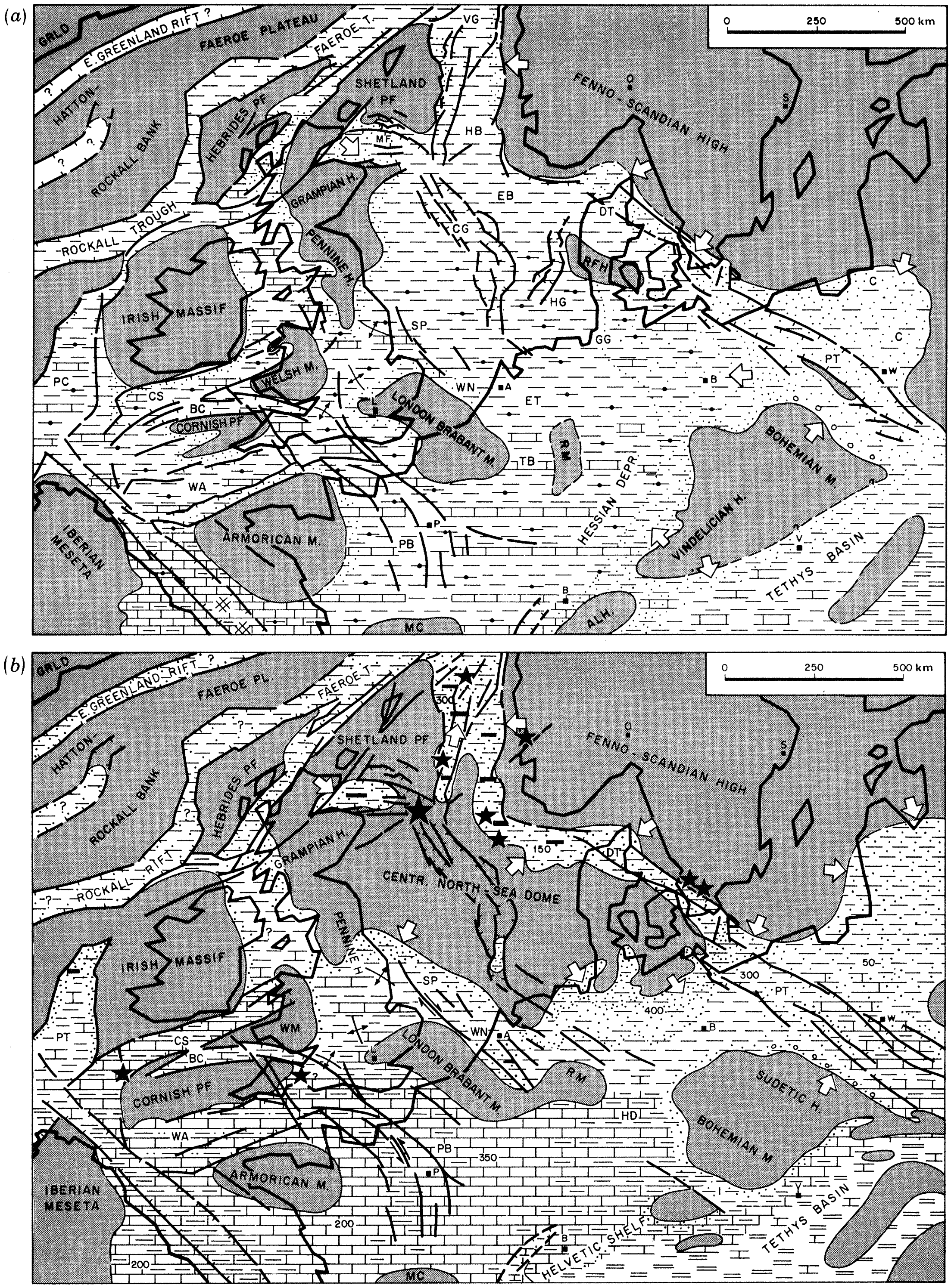

FIGURE 8. (a) Early Jurassic palaeogeography; (b) Bajocian–Bathonian palaeogeography. For key see figure 14.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Outside the North Sea area, the effects of the early mid-Jurassic rifting pulse were considerably less dramatic. The Polish–Danish Trough, as well as the Celtic Sea, Bristol Channel and Western Approaches grabens continued to subside differentially during the mid-Jurassic. There is no evidence for up-doming of these large rifts. Minor volcanic activity was restricted to the southwestern parts of the Celtic Sea Graben, southern England and the Fennoscandian Border Zone. Crustal extension across the Celtic Sea, Bristol Channel and Western Approaches grabens was compensated for by further left lateral movements along the Sticklepath, Normandie–Sennely and Pays-de-Bray faults.

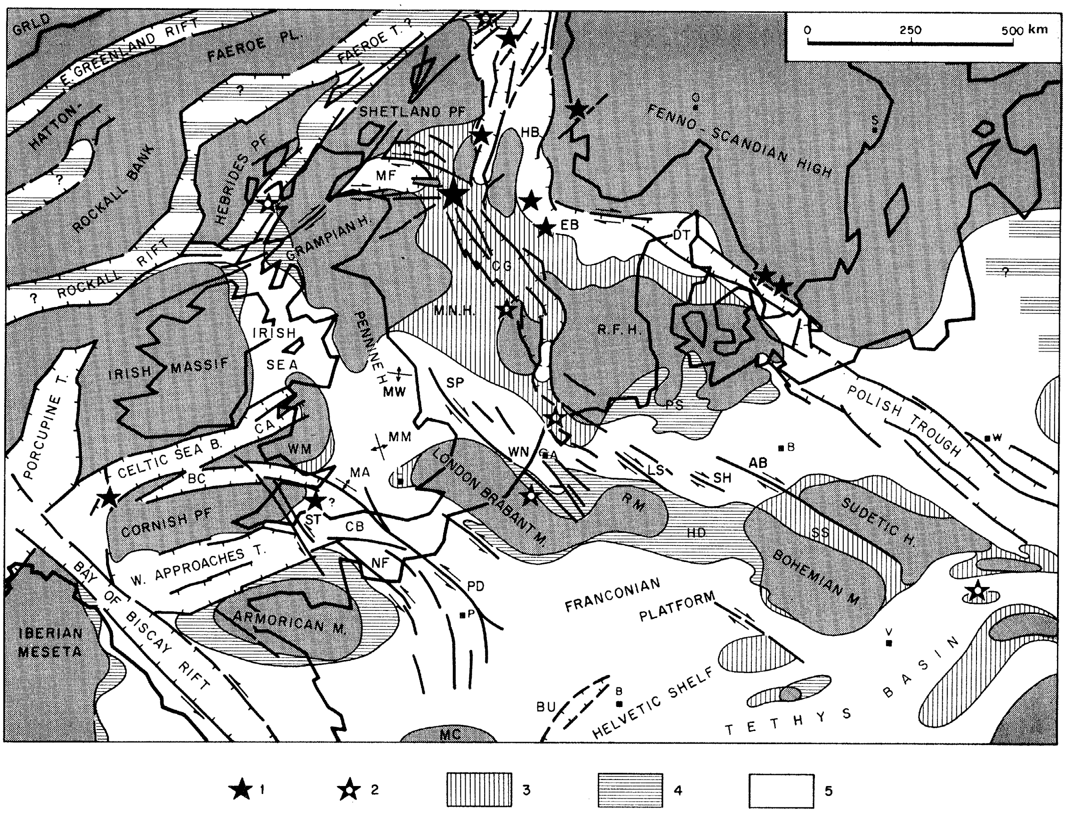

FIGURE 9. Mid and late Jurassic tectonic framework of western and central europe: 1, mid-Jurassic volcanics; 2, late Jurassic volcanics; 3, areas of non-deposition during the mid-Jurassic; 4, areas of non-deposition during the late Jurassic; 5, areas of continuous deposition during mid and late Jurassic.

Volcanic activity in the North Sea essentially ceased during the Bathonian. At the same time the North Sea rift dome began to subside and by late Jurassic time, deep-water conditions were established in much of the Viking and Central Graben (figure 9). Continued crustal extension across the North Sea rift was taken up at its southern end by a system of right-lateral wrench faults that controlled the differential subsidence of the Sole Pit, Broad Fourteens, West and Central Netherlands, Lower Saxony, sub-Hercynian and Altmark-Brandenburg basins ('marginal troughs' of Voigt (1962)). The progressive accentuation of these wrench-induced basins was accompanied by minor volcanic activity and the uplift of the Rhenish and Bohemian Massif whereby the latter became transected by the Saxonian Strait. At the same time the longstanding Hessian Depression was closed and the northeast–southwest-striking Horn Graben, Glückstadt Graben and the Emsland Trough became inactive.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The late mid-Jurassic and late Jurassic polarization of the European rift system can be related to a change in the overall stress pattern that was induced by crustal separation in the western Tethys. With this the northern shelves of the Tethys became tectonically quiescent and the evolution of northwest Europe became increasingly dominated by the Arctic – North Atlantic rift system in which crustal extension apparently accelerated during the late Jurassic, as reflected by the updoming of the triple junction between the Viking Graben and the West Norway – West Shetland/Faeroe Rift.

Late Jurassic crustal extension across the North Sea Rift and the rifts on the Celtic Sea – Western Approaches shelf was accompanied by a westward movement of the Anglo-Saxon Block (Ireland and the United Kingdom, including the London–Brabant Massif) relative to the Armorican Massif – Massif Central Block to its south and the Fennoscandian–Ringkøbing–Fyn block to its north. The resulting tectonic picture can be compared to a tooth being extracted from a jaw. Cracks that started to gape along the sides of its crown, the Anglo-Saxon Block, are represented by the North Sea Rift and the Celtic Sea – Western Approaches graben system, while slip planes developing along the roots of this 'tooth' correspond to the wrench faults and tension-gash basins that developed along the margins of the London–Brabant–Rhenish–Bohemian Block (figure 9).

(*c*) *Early Cretaceous rifting phases*

The early Cretaceous tectonic evolution of western and central Europe continued to be dominated by crustal stretching in the Arctic and North Atlantic domain whereby relatively little change occurred in its framework. Although the Bay of Biscay and the Rockall–Faeroe Graben were the principal rifting axes during the early Cretaceous continued crustal extension across the North Sea Rift and the Celtic Sea – Western Approaches graben system resulted in a sharp accentuation of the wrench-induced basins flanking the London–Brabant, Rhenish and Bohemian massifs. On the other hand the Horda–Egersund Basin and the Danish–Polish Trough subsided only mildly during early Cretaceous times (figure 10).

During the earliest Cretaceous a major rifting pulse, referred to as the Late Cimmerian tectonism, affected the entire northwest European and Arctic – North Atlantic rift system. It preceded the Neocomian onset of sea-floor spreading between the Azores and Charlie Gibbs fracture zones and was accompanied by a significant eustatic sea-level drop that is expressed in western and central Europe by a regional regression. During Valanginian to early Aptian times sea levels rose again, but this trend was temporarily reversed during the mid-Aptian. This regression coincides with the Austrian tectonic pulse that preceded the onset of sea-floor spreading in the Bay of Biscay and in the South Atlantic in areas north of the Walvis Ridge. A further regionally correlative, albeit minor, regression preceded the late Albian onset of sea-floor spreading in the Rockall Trough (Roberts *et al.* 1981 *a*).

In the Arctic – North Atlantic rift zone the Late Cimmerian pulse gave rise to the rapid subsidence of large rotational fault blocks in eastern Greenland (Surlyk 1975), the western Barents Sea (Rønnevik 1981) and on the West Norway shelf (Jorgensen & Navrestad 1981) and to the development of a significant submarine relief.

Also in the North Sea Rift the Late Cimmerian tectonism gave rise to the rapid subsidence of rotational fault-blocks along listric normal faults and a regional, largely submarine unconformity (figure 11). The resulting sea-floor relief was of the order of 1 km. In the Viking Graben, the tectonically undisturbed marine onlap of the early Cretaceous deep-water shales

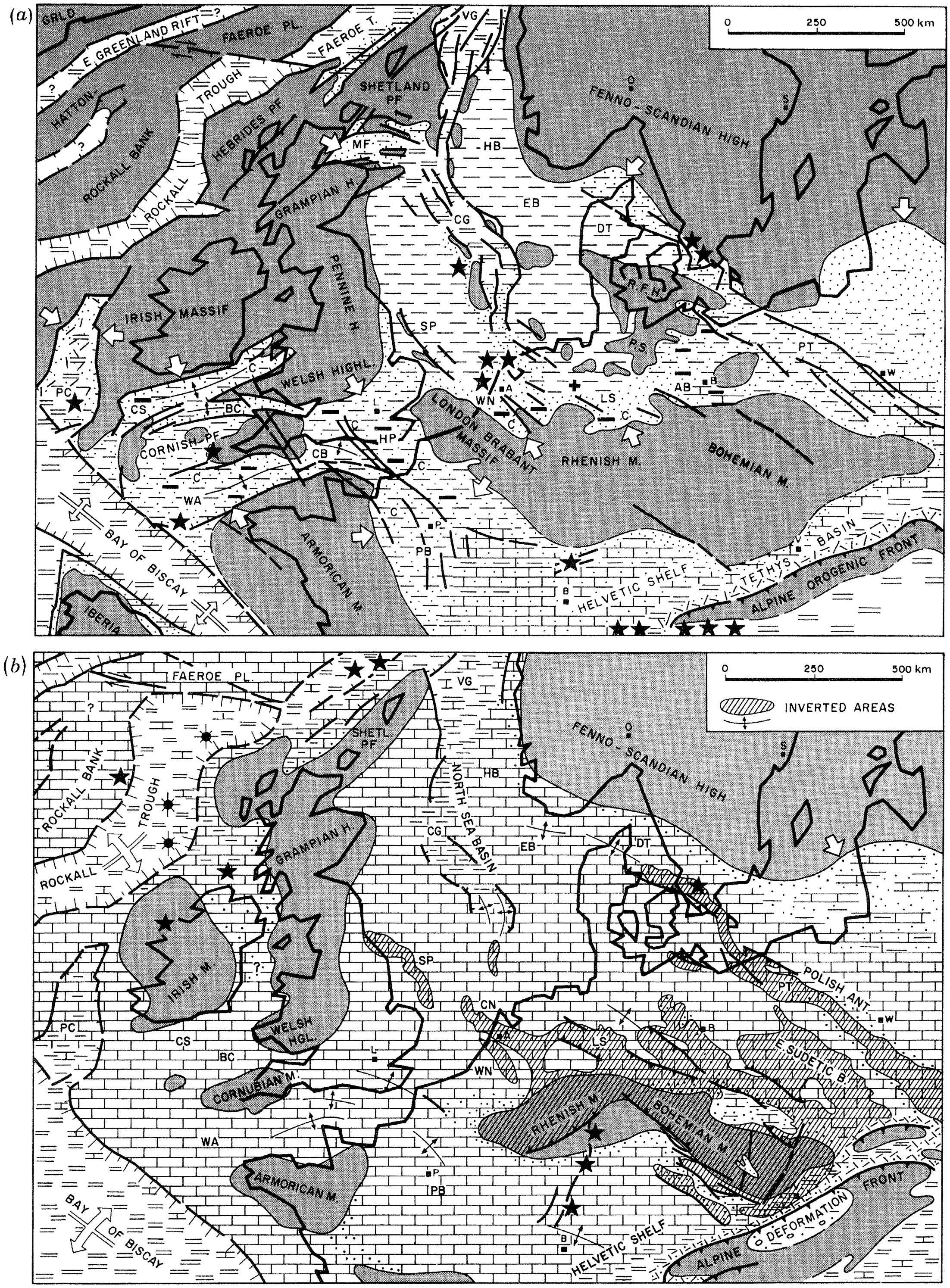

FIGURE 10. (a) Early Cretaceous palaeogeography; (b) late Cretaceous palaeogeography. For key see figure 14.

against the Late Cimmerian unconformity clearly illustrates that this rifting phase was very short-lived. In the central North Sea, early Cretaceous rift tectonics are less obvious owing to the overprinting effects of the intense diapirism of the Zechstein salt. The Austrian tectonic pulse finds little expression within the Viking and Central Graben, which continued to subside differentially during the Aptian and Albian. Early Cretaceous crustal extension across the Viking and Central Graben amounted to some 10 km but did not induce any major volcanic activity. Contemporaneous crustal stretching across the Moray Firth Rift gave rise to minor wrench movements along the Great Glen Fault.

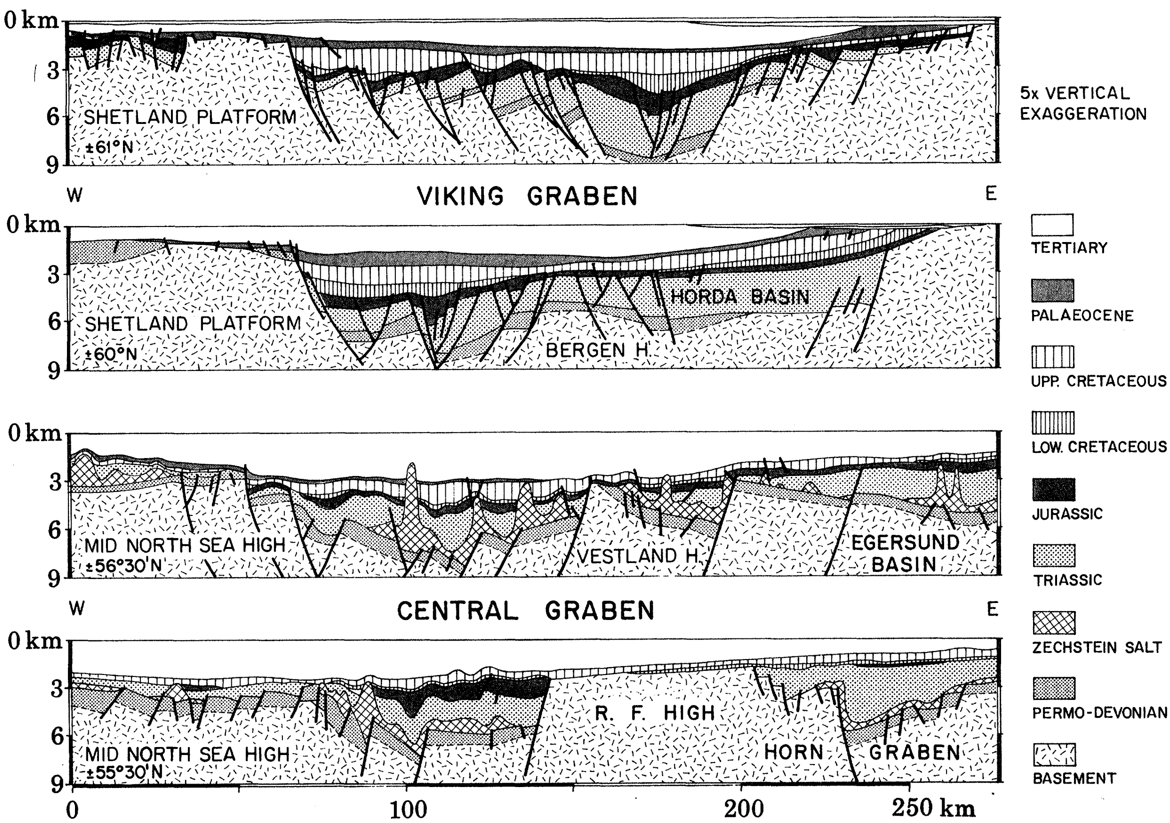

FIGURE 11. Schematic structural cross sections, northern and central North Sea. Approximate location of each section given by latitudes in western corner.

Early Cretaceous crustal stretching across the North Sea Rift was paralleled by the rapid subsidence of the wrench-induced basins flanking the London–Brabant, Rhenish and Bohemian massifs in which early Cretaceous series are developed in the clastic 'Wealden' facies (figure 10). Deep crustal fracturing associated with the Austrian tectonic pulse induced a number of short-lived volcanic centres in the Dutch offshore and the intrusion of batholiths in the Lower Saxony Basin.

In areas bordering the Bay of Biscay Rift the Late Cimmerian rifting and its associated sea-level drop caused the termination of the carbonate-dominated late Jurassic depositional régime and the onset of widespread Wealden-type clastic sedimentation.

Accelerated crustal extension preceding the onset of sea-floor spreading between Iberia and the Grand Banks was accompanied by uplifting and eastward tilting of the Iberian Meseta. The northward continuation of the Newfoundland–Lusitania rift is represented by the

Porcupine Trough, in the southern parts of which a geophysically defined major volcanic centre came into evidence during early Cretaceous time (figures 6 and 10). Crustal extension in the Lusitania–Newfoundland rift induced further left-lateral wrench movements in the Bay of Biscay Rift where they caused the rapid subsidence of the Parentis and Ardour sub-basin in the Aquitaine area and of the Duero Basin in northern Spain. In these relatively small basins early Cretaceous strata attain thicknesses of 4 km and more.

Associated with rift–wrench movements along the Biscay Rift, the Armorican Massif and the Western Shelves became uparched and tilted northeastward. This caused widespread truncation of Jurassic and earlier series, particularly on the Cornish Platform and on the Armorican Massif. From these highs erosion products were shed into the rapidly subsiding Celtic Sea, Bristol Channel and Western Approaches troughs, in which sedimentation resumed after a short break at the transition from the Jurassic to the Cretaceous.

Early Cretaceous paralic clastics reach a thickness of up to 2 km in the Celtic Sea Trough and 1.5 km in the Western Approaches Graben. Crustal stretching during the Neocomian was locally accompanied by volcanic activity. At the same time large rotational fault blocks, controlled by listric faults, subsided rapidly in response to crustal stretching along the shelf edge and on the continental slope of the Celtic Sea and Western Approaches. These fault blocks are unconformably overlain by undeformed late Aptian and younger strata. Crustal separation between Europe and Iberia and the onset of sea-floor spreading in the Bay of Biscay is thus dated as intra-Aptian (Montadert *et al.* 1977; De Charpal *et al.* 1978; Roberts *et al.* 1981*b*). In the Celtic Sea – Western Approaches area this intra-Aptian (Austrian) tectonic event corresponds to a distinct phase of block-faulting and wrench-induced basin inversion whereby regional uplifting and profound truncation of early Cretaceous and older series preceded the transgression of the Aptian Greensands.

(*d*) *Late Cretaceous and Cainozoic development of the North Sea Rift and the Atlantic shelves*

With the late early Cretaceous onset of sea-floor spreading in the Bay of Biscay and the Rockall Trough, the rifts on the western shelves became inactive and regional subsidence set in.

During the late Cretaceous, principal rifting activities were concentrated in the Labrador Sea, in Baffin Bay and possibly also in the Proto-Iceland Sea (Srivastava 1978; Gradstein & Srivastava 1980). At the same time rifting activities in northwestern Europe decreased substantially and regional subsidence of Atlantic shelves, the North Sea and Polish rift commenced, presumably in response to lithospheric cooling and sedimentary loading of the crust. A last tensional pulse affecting the North Sea area, but even more so the Atlantic shelves of Scotland and Ireland, occurred during the late Palaeocene and preceded the onset of sea-floor spreading in areas north of the Charlie Gibbs fracture zone (Kristoffersen 1977; Eldholm & Thiede 1980). This was associated with a significant sea-level drop and a major volcanic outburst that affected a broad belt extending from the Porcupine Trough over a distance of 1800 km to Kristiansand (western Norway) (figure 12).

After crustal separation in the Iceland and Norwegian–Greenland Sea, the evolution of the Atlantic shelves and the North Sea area was characterized by tectonic quiescence and regional subsidence.

In the North Sea late Cretaceous chalks and marls, attaining thicknesses up to 2 km, progressively infilled the topography of the Viking and Central Graben and onlapped against

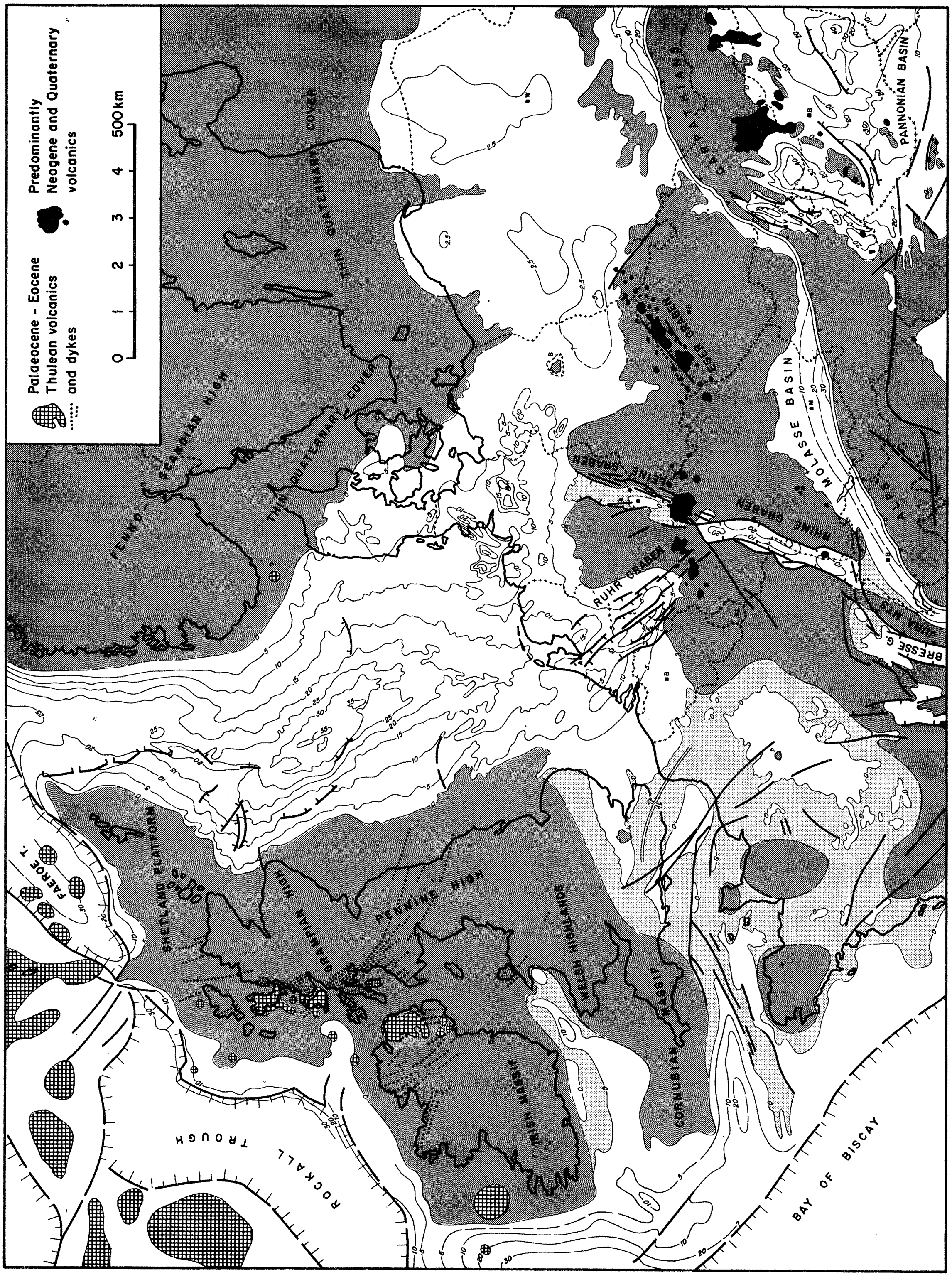

Figure 12. Isopach map of Cainozoic Series. Contour values in hundreds of metres.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

highs and the graben flanks. This probably had a loading effect on the crust, causing further regional downwarping. It is inferred that in the Viking and Central Graben, late Cretaceous sedimentation rates somewhat exceeded subsidence rates and eustatic sea-level rises; however true shallow-water conditions were not yet established in them. As syndepositional faulting played only a minor role during the late Cretaceous development of the North Sea Rift, it is concluded that crustal stretching was only of subordinate importance during its late rifting stage. Although the Laramide rifting pulse caused a reactivation of some of the border faults of the Viking and Central Graben, it is unlikely that this induced a significant reversal of the lithospheric cooling processes.

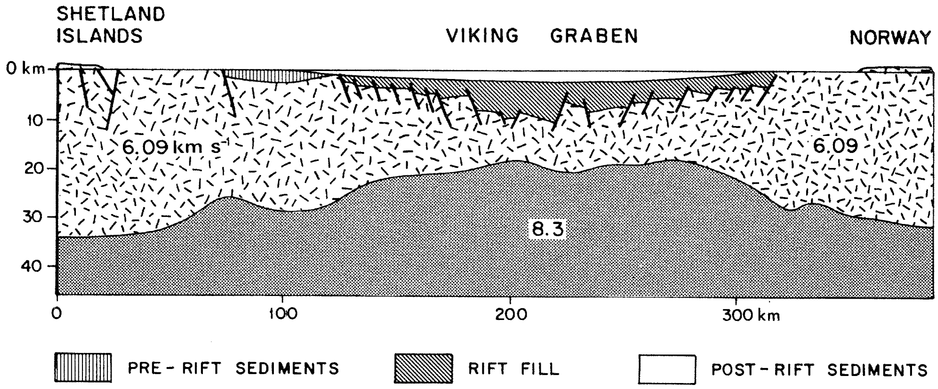

FIGURE 13. Crustal profile across Viking Graben.

The Cainozoic development of the North Sea Basin is characterized by further regional downwarping and the lack of syndepositional faulting. Cainozoic series reach a maximum thickness of 3.5 km in the central North Sea. Time stratigraphic units generally expand towards the basin centre (Ziegler & Louwerens 1979).

The Cainozoic Central North Sea subsidence maximum is probably related to an area of maximum crustal thinning (Donato & Tully 1981) and to the decay of a maximum thermal anomaly that was induced during its Jurassic and early Cretaceous rifting stage. Thermal contraction of the lithosphere probably controlled the Cainozoic post-rifting development of the North Sea Basin. During the Palaeocene and Eocene, subsidence rates and rising sea levels apparently exceeded sedimentation rates and caused the deepening of the basin. During the Oligocene, subsidence and sedimentation rates kept more or less in balance. During the Neogene, sedimentation rates exceeded the tectonic subsidence and the basin shallowed out rapidly. However, concomitant sedimentary loading of the crust accounted for an acceleration of the overall subsidence rates.

Gravity data give evidence for the presence of a mass excess beneath the low density sediments of the Viking and Central grabens (Donato & Tully 1981). The refraction profile given in figure 13, which crosses the northern North Sea, clearly illustrates that the crust–mantle interface rises from a depth of 30–35 km beneath Norway and the Shetland Islands to about 20 km under the Viking Graben in which sediments reach a thickness of 8–10 km; correspondingly, its continental crust is 60–70 % thinner than beneath the Shetland Platform and Fennoscandia. Throughout this refraction profile the upper mantle displays a normal velocity of 8.1–8.3 km s^{-1}.

Based on these data and on a quantitative analysis of the late Cretaceous and Cainozoic subsidence of the North Sea Basin, Sclater & Christie (1980) propose that thinning of the crust under the Viking Graben was accomplished during the Mesozoic by stretching it by a factor 1.8–2.0. This would correspond to a crustal extension by 75–100 km. Multichannel reflexion data show, however, that extension of the sediments by faulting is at the Jurassic level only of the order of 10–15 km. As the base of the Triassic series can only be mapped locally in the Viking Graben, the amount of crustal extension at the base of the syn-rift sediments cannot be readily determined. However, judging by the geometry of the individual fault blocks and the lack of significant divergence of Triassic reflectors, it is very unlikely that the total amount of Mesozoic crustal extension exceeds 20–25 km; this would correspond to a stretching factor of only 1.2 to a maximum of 1.3. Similarly the amount of crustal extension postulated by the stretching model for the Witchground and Buchan Graben (Christie & Sclater 1980; Christie, this symposium) is at variance with the amount of extension observed on reflexion seismic data.

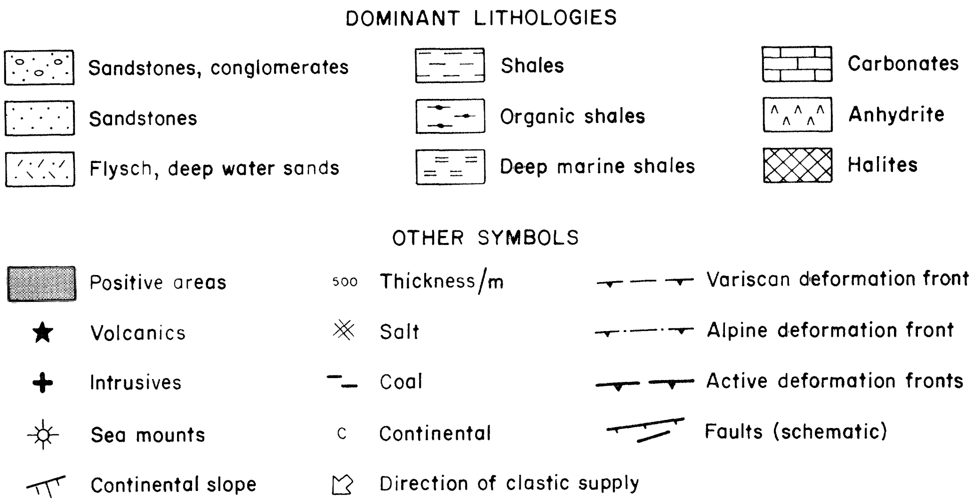

FIGURE 14. Key to palaeogeographic maps.

For the Danish part of the Central Graben and the Horn Graben, reflexion data indicate that at the base Zechstein level the combined amount of crustal stretching is about 10 km, to a maximum of 15 km. This is compatible with the values determined for the Viking Graben. A considerably greater amount of crustal extension for the central North Sea, for which gravity data indicate a wide zone of thinned crust, is, however, difficult to visualize in view of the overall geometry of the North Sea Rift. Yet the deepest parts of the Cainozoic North Sea Basin do coincide with the axis of the Central Graben and the largest gravity anomaly (Donato & Tully 1981).

Results of these preliminary investigations indicate that crustal thinning across the North Sea Graben system was achieved during its Mesozoic rifting stage not only by mechanical stretching, but partly also by thermally induced physico-chemical processes affecting the lower crust. These processes, which are vaguely circumscribed as 'subcrustal erosion', are apparently irreversible. Moreover they appear to have been more effective in the area of the mid-Jurassic central North Sea rift dome than beneath the Viking Graben.

The late Cretaceous and Cainozoic development of the Atlantic shelves of Ireland and Scotland differs from that of the North Sea in that lithospheric cooling processes were temporarily reversed by the Palaeocene – early Eocene Thulean volcanism or only set in after its extinction. Moreover, as the thickness of the crust under the different parts of the Atlantic shelves varies considerably and as sediment availability to these shelves was far from uniform, their Cainozoic subsidence patterns show great variations. For instance a Cainozoic clastic wedge, up to 2 km thick, progrades from the West Shetland shelf into the Faeroe Trough. Also, the Porcupine Trough with its thinned crust subsided rapidly during the Cainozoic; however, owing to a limited clastic supply Neogene subsidence rates outpaced sedimentation rates.

On the other hand, the Hebrides and Northwest Irish shelves, which are characterized by only limited Mesozoic extension, were largely bypassed by Cainozoic clastics.

7. Late Cretaceous and Cainozoic foreland compression

The early late Cretaceous development of the Polish–Danish Trough and of the wrench-induced Sole Pit, West and Central Netherland, Lower Saxony, Sub-Hercynian and Altmark-Brandenburg basins was characterized by regional downwarping rather than by sharp differential subsidence. In the course of the Senonian, subsidence of these troughs as well as of the southern parts of the central North Sea Graben was interrupted and reversed. The sedimentary fill of these basins became folded, uplifted and subjected to various degrees of erosion (Sub-Hercynian phase). During late Senonian to Danian time the sea advanced again over the rapidly degraded fold axes and deposited the Upper Chalk series on the in places deeply truncated Lower Chalk and older series. A second, generally more intense, deformation phase affected the same basins during the late Palaeocene (Laramide phase) (figure 10).

The structural style of these previously tensional basins indicates that their late Cretaceous and early Tertiary inversion was induced by compressional or wrench movements, or both. The intensity of inversion generally decreases with increasing distance from the Alpine deformation front. The structural relief created by this basin inversion amounts at the late Cretaceous level, for instance, to 1.5 km in the Sole Pit Basin, 2.5 km in the Lower Saxony Basin and 2–3 km in the Polish Trough.

Concomitant with the inversion of these basins, the Rhenish and the Bohemian Massifs became dissected and in part uplifted along a set of wrench and steep reverse faults whereby the reactivation of Stephanian–Autunian faults probably played a major role.

The subcrop pattern of the Mesozoic series below the Tertiary sediments of the Carpathian foredeep and the Eastern Molasse Basin illustrates that also these areas were strongly deformed during late Cretaceous and early Tertiary time and that major structural elements extend well under the Carpathian and Alpine nappes.

Late Cretaceous and early Tertiary compressional and wrench-induced deformations are restricted to the Carpathian and northern Alpine foreland and fade out to the west (figure 10). For instance the Channel and Hampshire Basins were only very mildly deformed during the Palaeocene compressive phase. Their main inversion, similar to the Western Approaches, Celtic Sea and Bristol Channel Troughs, is dated as Oligocene and Miocene (figure 12).

The onset of the late Cretaceous and early Tertiary compressional foreland deformation coincides with major orogenic events in the Carpathians and the Eastern Alps and probably reflects the collision between the Central Carpathian Massif and the Italo-Dinarid promontory with the fractured European craton. Compressional stresses exerted on the latter gave rise to the tilting and uplifting of the Variscan massifs and the inversion of major Mesozoic troughs at distances up to 1000 km to the north of the present Alpine deformation front. The crustal configuration of the strongly inverted Polish Trough (Guterch *et al.* 1976) shows that the thinned crust of this previously tensional basin was mechanically thickened during its inversion to the degree that it reached thermal and isostatic equilibrium.

From this it is inferred that compressional foreland deformation causing the inversion of rifts and the uplifting of basement blocks along reverse and wrench faults involves the entire crust and therefore requires a decoupling between it and the upper mantle.

In the northern Alpine and Carpathian foreland no further compressional deformations occurred during the post-Palaeocene orogenic phases of the Alpine fold belt. With the onset of the Eocene, elastic down-flexing of the foreland crust under the load of the advancing nappes (onset of underplating?) gave rise to the development of the Carpathian and Alpine foredeeps. This was accompanied by intense basin-parallel block-faulting of the down-bent foreland crust. It is reasoned that the lack of further compressional deformation of the northern Alpine and Carpathian foreland reflects a decoupling between the European craton and the overriding thrust masses at the Carpathian and the East Alpine A-subduction zones. On the other hand, strong coupling at the Central and West Alpine A-subduction zones induced the late Oligocene and Miocene inversion of the rifts of the Celtic Sea – Western Approaches shelf.

8. Cainozoic rifts of the Alpine foreland

During the late Eocene and early Oligocene, the volcanic rift system of the Limagne, Bresse, Rhine, Ruhr, Leine and Eger grabens came into evidence as entirely new tectonic features on the face of western and central Europe (figure 12). The Limagne and Rhine–Leine grabens and possibly also the Eger Graben are superimposed on late Carboniferous – early Permian fractures. The Ruhr Graben is partly superimposed on the inverted West Netherlands Basin.

This complex graben system remained intermittently active until the present. Its evolution is contemporaneous with the Alpine late orogenic phases, and parallels the Neogene collapse of the Mediterranean and the Pannonian Basin and the inversion of the Channel area and of the Western Approaches, Bristol Channel and Celtic Sea troughs.

Volcanic activity set in the Rhine Graben simultaneously with its initial subsidence during the late Eocene, in the Massif Central in the course of the Oligocene and in the Eger Graben during the late Oligocene. These volcanics display an alkaline, mafic–felsic bimodal composition.

Upwarping of the Rhenish Massif at the triple junction between the Rhine and Leine and Ruhr Graben began during the early Miocene and was followed by the mid and late Miocene extrusion of extensive trap basalts. Uplifting of the Vosges – Black Forest rift dome at the southern end of the Rhine Graben started somewhat earlier but apparently also postdates the onset of graben subsidence. The Massif Central became updomed during the late Miocene and Pliocene.

The different parts of the Bresse–Rhine–Ruhr–Leine rift subsided only intermittently during the Neogene and Quaternary; this reflects changes in the regional stress pattern. During the Miocene, the Bresse Graben and the southern parts of the Rhine Graben ceased to subside differentially (Rat 1978; Illies 1978); this coincides with the main inversion phase of the Mesozoic troughs in the Celtic Sea – Western Approaches and Channel areas. During the Pliocene, however, the Bresse Graben once more began to subside, while the evolution of the Rhine Graben was controlled by sinistral shear motions. During the Pliocene the southern margins of the Rhine Graben and the eastern rim of the Bresse Graben were overridden by the frontal thrust sheets of the Jura Mountains. At present the Rhine Graben is being deformed by sinistral strike-slip movements. In contrast, the Ruhr Graben is currently subsiding actively in response to tensional stresses (Illies & Greiner 1978; Ahorner 1978). This graben feathers out to the northwest in the Dutch onshore areas. Similarly, the currently inactive Leine Graben dies out to the north at the edge of the North German lowlands.

Cainozoic series reach maximum thicknesses of some 3 km in the Rhine Graben and 2 km in the Bresse Graben.

Geotectonic processes that governed the development of the Cainozoic rifts of western and central Europe are the subject of much speculation.

Regional crustal extension apparently preceded the development of discrete hot-spots that are marked by upper mantle anomalies as observed under the Massif Central, the Vosges – Black Forest dome and possibly the Rhenish Massif (Perrier & Ruegg 1973; Edel *et al.* 1975; Giese 1978). For example, crustal extension acrosst he Rhine Graben is estimated to amount to some 5 km and is considerably larger than could result solely from the uparching of a rift dome in response to the emplacement of an asthenolith (Laubscher 1970). Yet the early onset of volcanic activity distinguishes the Cainozoic rifts from the Mesozoic grabens of Europe.

Viewed in a broader framework, the Cainozoic rifts in the Alpine foreland may be considered as forming part of the Neogene Mediterranean collapse system that presumably developed in response to a reorientation of the convergence direction between Africa and Europe (Laubscher 1974; Biju-Duval *et al.* 1977). It is conceivable that this reorientation of the regional stress field was also responsible for the interplay of tensional and compressional tectonics in the Alpine foreland.

Alternatively, the volcanic rifts of western and central Europe could be regarded as forming the northern extension of the East African – Red Sea and Libyan–Tyrrhenian rift systems, which became active during the early Oligocene and the Miocene (Richter-Bernburg 1974; Illies 1974).

A third model, which is based on the Himalayan setting, visualizes the Rhine–Bresse Graben as so-called 'impactogens' (Sengör *et al.* 1978; see also Molnar & Tapponier 1975). This model is, however, not fully compatible with the evolution of the Rhine and Bresse Grabens, in which periods of active subsidence appear to alternate with the main compressional events in the Alpine fold belt.

None of the above geotectonic processes is able to explain fully the development of the Cainozoic rift in the Alpine foreland. Thus some combination of these processes may have to be envisaged whereby one or the other processes was variously, in time and space, the dominant mechanism controlling basin subsidence and the initiation of volcanic activity.

Overall, the Neogene and Quaternary development of the Alpine domain and its foreland may be interpreted as heralding the break-up of the current continent assembly.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

9. Conclusions

In Europe, rifts have developed through time in a number of megatectonic settings.

Rifting, leading to the break-up of continents and the opening of major oceanic basins, for instance on the scale of the Atlantic, is the most important process of graben formation. In this setting the rifting stage preceding crustal separation can be relatively short, as with the central Atlantic (40 Ma) or can be long-lived, as in the Norwegian Greenland Sea (270 Ma).

Wrench faulting associated with the translation of either rift systems or orogenic belts, dependent on fault geometries, can induce the rapid subsidence of pull-apart or tension gash basins, or both. Pull-apart grabens at the termination of wrench faults, as for instance the Oslo Rift, can be highly volcanic. Subsidence of tension-gash basins (e.g. Lower Saxony and Parentis Basin) may or may not be associated with short-lived igneous activity.

Back-arc rifting is thought to have played a significant role in the development of the Variscan geosynclinal system. Mechanisms governing back-arc rifting and sea-floor spreading are still the subject of much debate. In the same way that compressional and extensional phases appear to alternate in an island arc setting, back-arc rifts are prone to destruction, particularly under the impact of continent–arc collision.

Wrench faulting and rifting of the Himalayan type (Molnar & Tapponier 1975), which are thought to be the consequence of continent–continent collision, do not appear to play a major role in Europe. However, intraplate compressional deformation involving the inversion of rifts and the uplifting of basement blocks was of major importance during the Variscan and Alpine diastrophism.

Elastic down-flexing of the foreland plate under the weight of the advancing nappes controlled the development of the Variscan and Alpine foredeep basins. The subsidence of such basins can be associated with tensional deformation of the upper crust whereby synthetic faults predominate, as for instance in the Molasse Basin.

Regardless of which megatectonic setting rifts formed under, their subsidence is governed by lithospheric thinning and sedimentary loading of the crust. During rifting phases the continental crust is stretched and thinned in response to regional extension that is presumably induced by convection currents in the asthenosphere, which drive the lithospheric plates apart. Necking of the continental crust is attained at shallow levels by listric normal faulting and at deeper levels by ductile flow. However, the amount of crustal thinning observed, for instance across the North Sea rift and the Celtic Sea – Western Approaches shelf (Avedik *et al.*, this symposium), cannot be fully accounted for by the crustal stretching model. It is therefore inferred that during periods of active crustal extension, thermally induced physico-chemical processes affect the lower crust and contributes significantly to crustal thinning; these processes appear to be irreversible.

Many rifts are totally non-volcanic or show only a very low level of volcanism. Other rifts display a high level of volcanic activity right from the onset of crustal extension or become temporarily volcanic after an initial stage of non-volcanic subsidence. A high level of volcanism is generally associated with a high rate of crustal extension and the uplifting of a wide-radius rift dome that is centred over the axis of the rift. Uplifting of a rift dome can cause a substantial reversal in the subsidence pattern of a rift and generally induces extensive erosion mainly over the rift flanks; on a restricted scale this can contribute to crustal thinning. Crustal extension resulting from the uplifting of a rift dome is, however, rather small and amounts for instance to some 200 m for a dome with a width of 200 km and a height of 3 to 4 km (Artemjev & Artyushkov 1971).

Upwarping of such a rift dome is caused by the emplacement of a low-density, low-velocity upper mantle anomaly at the crust–mantle interface; the development of such an anomaly is presumably caused during periods of intensified crustal extension by failure of the lithosphere or by thermally induced lower mantle diapirism, or both (Osmaston 1971, 1973, 1977; Bott 1976).

The physical properties of such upper mantle anomalies, also referred to as 'asthenoliths', 'rift pillows' or 'rift cushions', can be explained by melting processes. Magmas intruding the crust from an asthenolith may eventually reach the surface where they display at first the chemical characteristics of a typical alkaline initial rift volcanism. In time and with persisting crustal extension this volcanism will gradually change over to a tholeitic basalt type. This gives rise to the bimodal felsic–mafic alkaline suites that characterize the volcanism of continental rifts (Martin & Piwinski 1972).

Triple junctions, where crustal extension is most intense, are likely places for an early manifestation of rift volcanism (e.g. Rhine Graben and North Sea Rift). However, volcanic activity is not necessarily restricted to the actual rift zone; yet the occurrence of lateral volcanic centres appears to be limited to the area of the rift dome and, with this, to the confines of the correspondent asthenolith.

Asthenoliths are thermally unstable upper mantle anomalies and are resorbed in the latter upon cooling once crustal extension has fallen below a certain rate or has ceased altogether. Correspondingly, beneath thermally stabilized palaeorifts the upper mantle displays a normal density of about 3.3 and velocities of 8.1–8.3 km s^{-1}.

Following crustal separation the subsidence of the newly formed 'passive continental margins' is controlled by lithospheric cooling and sedimentary loading of the crust. Similar mechanisms govern the subsidence of rifts that have become inactive (Sleep 1973, 1976; McKenzie 1978; Sclater & Tapscott 1979; Watts & Steckler 1981; Jarvis & McKenzie 1980; Royden *et al.* 1980).

The amount of subsidence caused by lithospheric contraction is controlled by the magnitude of the thermal anomaly that was induced during the lithospheric stretching – crustal separation stage. It is inferred that maximum thermal anomalies are induced during continental separation and that thermal anomalies induced by rifting are comparatively smaller. Correspondingly, the post-separation development of a passive continental margin probably reflects the decay of a maximum thermal anomaly, while the subsidence of inactive rifts is probably governed by the decay of smaller thermal anomalies. On the other hand, the post-rifting development of highly volcanic rifts that were underlain by an asthenolith during their rifting phase is probably associated with the decay of a larger thermal anomaly than of non-volcanic rifts. In the post-rifting subsidence pattern of volcanic rifts the resorption of the asthenolith into the mantle by cooling processes presumably plays a significant role. Moreover, erosion of upper crustal rocks over the crest of a rift dome can contribute to crustal thinning and thus will be reflected in the subsidence of an inactive rift.

A further aspect that has to be considered in quantitative subsidence models of rifts is the fact that crustal extension and concomitant sub-crustal thinning can take place intermittently over very long periods. In long-lived rifts, thermal anomalies induced by, and associated with, crustal extension can already start to decay during periods of decreased rate of crustal stretching. Thus the thermal anomaly associated with a rift may not be at its maximum when crustal extension terminates altogether and the respective rift becomes inactive. Similarly, late rifting pulses may interrupt and even reverse the normal lithospheric cooling processes. This is illustrated by the evolution of, for instance, the North Sea Rift in which the maximum thermal anomaly was presumably induced during the early Bajocian, while significant crustal extension persisted into early Cretaceous times. On the other hand, the evolution of the West Shetland–Faeroe Rift is characterized by a late Jurassic thermal surge and a second late Palaeocene – early Eocene one.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Discussion

SIR PETER KENT, F.R.S. Ziegler has suggested that the Bajocian–Bathonian mid North Sea dome, extending southwards from the Forties region across the mid North Sea High into the southern North Sea, had an amplitude of 2 km. This amplitude is difficult to reconcile with the sections across the oil fields, which are very well constrained. The missing sediments have a thickness of only 60 m at the most, and there is no evidence for the formation of a huge bulk of detritus of this age, which would have been produced by levelling such a structure.

P. A. ZIEGLER. Evidence in support of the postulated Bajocian–Bathonian rift dome in the central North Sea is provided by (*a*) the facies development of the Liassic series and their subcrop pattern against the base Bajocian (Mid-Cimmerian) unconformity (Ziegler 1980, 1981) (*b*) the distribution and facies development of the Bajocian and Bathonian series (see figure 8), and (*c*) in the central North Sea the progressive onlap of the transgressive Callovian, Oxfordian and Kimmeridgian series against the Mid-Cimmerian unconformity.

The importance of the Mid-Cimmerian unconformity is illustrated by the third cross section from the top on figure 11. This cross section extends from 56° N 1° E on the mid North Sea High via the Auk and Ekofisk fields to 57° N 6° E in the Egersund Basin. Throughout this cross section the base of the Jurassic series corresponds to the Mid-Cimmerian unconformity. While Bajocian and Bathonian series occur in the Egersund Basin, Callovian, Oxfordian and locally even Kimmeridgian strata transgress in the Central Graben, on the Vestland High and the Mid North Sea High over Triassic and older sediments. The angular relation between the series underlaying and overlaying the mid-Cimmerian unconformity is clearly evident on reflexion seismic data and indicates that the Central North Sea rift dome near its culmination along the Central Graben had a structural relief of some 2–3 km (see particularly the western part of Egersund Basin and Vestland High).

From this dome vast amounts of sediments were removed, particularly during Bajocian and Bathonian times. While paralic and deltaic series accumulated along the margins of this high, finer clastics were dispersed in the Arctic – North Atlantic rift, in the southern North Sea and in northern Germany.

No attempt has been made to establish a material balance between the volumes of sediments removed from the postulated rift dome and the volumes of sediments deposited in adjacent areas during times of its emergence. Uncertainties of such volumetric estimates are likely to be very large and presumably will not provide an overriding constraint to the palaeogeographic and seismostratigraphic observations that support the existence of an early mid-Jurassic rift dome in the central North Sea.